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NONDESTRUCTIVE EVALUATION FOR DAMAGE TOLERANCE LIFE MANAGEMENT OF COMPOSITE STRUCTURES (POSTPRINT)

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14. ABSTRACT ***(Maximum 200 words)***
Polymer matrix composites (PMCs) are experiencing a growth in their use for civilian and military aircraft. However, the certification process for PMCs leads to new requirements for nondestructive evaluation/inspection (NDE/I). For example, in metallic structures current practice as defined in MIL STD 1530Dc1 uses slow crack growth analysis requiring the NDE/I technique to have a defined probability of detection (POD) curve to enable risk calculations. However, certification processes used to date for PMCs are closer to safe-life methods. However, there is a desire to alter the approach for managing PMCs structures in the US Air Force (USAF) to follow slow damage evolution criteria as is done for metallic structures today. To realize this desired capability, predictive modeling is being developed for slow damage evolution in PMCs. As a key input to these models, metrics of damage are required from NDE/I-based methods that characterize the geometry of the defects. Explored technical approaches include conventional pulse-echo methods, including resolution of tip diffraction from delaminations at the individual ply level, but amplitudes of these responses are quite small. An alternative approach uses localized single-sided pitch-catch methods to evaluate ultrasound propagating through and around a damaged region.

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Nondestructive Evaluation for Damage Tolerance Life Management of Composite Structures

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Abstract. Polymer matrix composites (PMCs) are experiencing a growth in their use for civilian and military aircraft. However, the certification process for PMCs leads to new requirements for nondestructive evaluation/inspection (NDE/I). For example, in metallic structures current practice as defined in MIL STD 1530Dc1 uses slow crack growth analysis requiring the NDE/I technique to have a defined probability of detection (POD) curve to enable risk calculations. However, certification processes used to date for PMCs are closer to safe-life methods. However, there is a desire to alter the approach for managing PMCs structures in the US Air Force (USAF) to follow slow damage evolution criteria as is done for metallic structures today. To realize this desired capability, predictive modeling is being developed for slow damage evolution in PMCs. As a key input to these models, metrics of damage are required from NDE/I-based methods that characterize the geometry of the defects. Explored technical approaches include conventional pulse-echo methods, including resolution of tip diffraction from delaminations at the individual ply level, but amplitudes of these responses are quite small. An alternative approach uses localized single-sided pitch-catch methods to evaluate ultrasound propagating through and around a damaged region, such as typical damage from impacts. It uses the signal transmitted through damaged regions to extract features indicating matrix cracking or internal geometric attributes of delaminations that supplement the conventional one-sided pulse echo measurement. The methods includes using model-based methods and feature extraction approaches. Initial results show significant promise and damage state verification is obtained from destructive methods based on serial sectioning. This provides ground truth for measurements and is a reference for metrics of performance. With this capability, the Building blocks are in place to realize slow damage growth damage tolerance for PMC structures.

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1 Introduction

The integrity, or safety, of US Air Force structures is governed by the Aircraft Structures Integrity Program (ASIP) and requirements for this process in the design, development, testing, and sustainment of structures is defined in Military Standard (MIL STD) 1530Dc1 [US Department of Defense 2016]. ASIP was established in the late 1950s in response to multiple structural mishaps, including structural failures that led the loss of aircraft [ASC-TR-2010-5002]. Initially, the ASIP process used probabilistic approach to establish the service life capability of aircraft, frequently called a "safe-life" approach.

However, in the late 1960's and early 1970's several additional major mishaps occurred that included loss of aircraft and crew for aircraft far short of their qualified "safe-life" [ASC-TR-2010-5002]. As an example, one aircraft had a catastrophic failure at less than five percent of its design service life, indicating the designs were not tolerant of manufacturing and/or service induced defects. These mishaps led to the development of the Durability and Damage Tolerance (DADT) approach for managing the integrity of USAF aircraft structures which was formally integrated into ASIP in 1975.

One key element of DADT is the design of structure to tolerate detects for some inspection-free period of service usage, providing the USAF a safety limit for each critical area in the aircraft. As a representative example, for metallic structure the safety limit is the time, in flight hours, required for a fatigue crack to grow from either an assumed initial flaw size, or the inspectable flaw size, to a critical size. Inspections are scheduled to occur at a time equal to one-half the determined safety limit. As a measure of success for aircraft designed and/or maintained using a damage tolerance approach, the USAF destroyed aircraft rate due to structural reasons is between one and two destroyed aircraft per ten million flight hours accumulated in the fleet [ASC-TR-2010-5002]. This is at least ten times lower than the overall USAF destroyed aircraft rate due to all causes except combat related [ASC-TR-2010-5002]. Accordingly, USAF believes the damage tolerance approach incorporated into ASIP in the 1970s continues to be the cornerstone for protecting the safety of the USAF fleet.

DADT is successful for metallic structures due to, in part, the significant advancements in fracture mechanics of aerospace metals and applications after the initial experiences of structural failures of aircraft in the 1950's. This enables fatigue crack growth to be predicted as a function of stress from loads experienced during use. The accuracy of these predictions is affected by, amongst others, such variables as localized fit up stresses that can change due to numerous factors during the life of an aircraft, and the fidelity of the systems that record loads during flight. The accuracy of loads monitoring has improved with the transition from loads and environmental spectrum surveys (LESS) to individual aircraft tracking (IAT) which has improved predictions for fatigue crack nucleation and growth, especially for larger fleets of aircraft types.

The increased use of carbon fiber reinforced polymer matrix composites (PMCs) has evolved to include structural elements in addition to non-structural components. The growth in applications has led to a desired capability to align the life management of these materials to that of metallic structures. Current processes for PMC components follow a version of "safe-life" methods which relies on results of a laboratory test of a full-scale airframe subjected to loading that simulated the operational service environment of the aircraft [ASC-TR-2010-5002]. The safe-life of the aircraft is obtained by dividing the number of successfully test simulated flight hours by a scatter factor. For PMCs elements of the environment in this testing include humidity and temperature.

A challenge for this certification approach is structures where there is a desire to extend life [Mollenhauer and Flores 2015], especially when the composite components are integrated with metallic components in a design. Therefore, there is a strong interest in managing the life of PMC components using a DADT approach. To realize this capability, two critical elements are needed that are under development. The first is a slow damage growth model for PMCs to enable prediction of flaw nucleation and growth, including growth from unintended impact events that occur during use. The second is the NDE technique that can detect and size damage in PMCs with sufficient fidelity to enable the slow damage growth models to occur as a function of the type and extent of damage. These capabilities are more complex that their equivalents for metals due to the variations in the PMC lay-ups as a function of intended use and geometry.

In addition, the NDE methods require reproducible detection for fatigue cracks, typically measured by a probability of detection (POD) study as described in Military Handbook (MIL HDBK) 1823A [US Department of Defense 2009]. Similar capability is required for NDE detection of flaws in PMCs, but the flaws require characterization in three dimensions to reflect the complex three dimensional shape of damage in PMCs. This is a new domain for NDE-based methods as some of the geometry of the flaws results in defective regions being hidden under other defective areas in the material. Thus, new methods are required for both slow damage growth modeling and three dimensional flaw characterization. Progress to realize these capabilities are described in the following two sections.

2 Slow Damage Growth Modeling

The delamination onset and propagation investigation in composite laminates has been a critical research topic for several decades and is the subject of many reviews [e.g. O'Brien 1990; Tay 2002; Pagano and Schoeppner 2000]. Previous efforts have explored satisfactory methods to describe isolated damage modes. Significant achievements in practical application of the virtual crack closure technique (VCCT) [Krueger 2004] to delamination propagation in laminated composite panels, both in static and fatigue regimes, were recently reported by Deobald and co-authors [Deobold et al. 2007]. Although the delamination failure mode is of great practical importance, it cannot be considered in isolation from other less critical damage modes, e.g. matrix cracking [Hallet et al. 2008]. Depending upon the layup and loading profile, the delamination propagation can be precipitated by matrix crack formation, which can drastically affect its propagation. Several scenarios directly influencing the damage tolerance assessment are possible: matrix cracking can temporarily arrest the delamination, it can divert the delamination to a different interface, and/or it may cause an avalanche of multiple delaminations through the thickness of the part.

Availability and rapid increase of computer power has enabled recent successes in the development of the discrete damage modeling (DDM) technique, which is based on the direct simulation of displacement discontinuities associated with individual instances of matrix cracking occurring inside the composite plies, and delaminations at the interfaces between the plies. These methods employ variants of eXtended Finite Element Methodology (X-FEM) [Moes et al. 1999] and its regularized implementation (Rx-FEM) [Iarve et al. 2011; Mollenhauer et al. 2012; Swindeman, at.al. 2012] in particular. The Rx-FEM method allows modeling the displacement discontinuity associated with individual matrix cracks in individual plies of a composite, without regard to mesh orientation, by inserting additional degrees of freedom in the process of the simulation. The propagation of the mesh independent crack is performed using the cohesive zone method. The kinematic aspect of the technique does not require any modification for fatigue loading, however, the constitutive component does.

As a representative example of the capability of this modeling approach, a two-step testing of the simulation to predict static and fatigue performance was performed. The following is a subset of the second phase, which was devoted to fatigue loading. Each phase consisted of a blind and a corrective stage. The fatigue damage extent, laminate stiffness degradation, and residual tensile/compressive strength of IM7/977-3 laminates were predicted and compared to experimental data. Three different layups [0/45/90/-45] 2S, [30/60/90/-60/-30]2S and [60/0/-60]3S, each with a 6.35 mm central open hole, were modeled and tested under various levels of fatigue cycles (all at R = 0.1). Each laminate was inspected with X-Ray computed tomography (CT) after 200,000 cycles. The details of the model/experiment comparisons for the [60/0/-60]3S laminate are presented here.

Figure 1 displays the delamination pattern on each interface starting from the laminate top surface from left to right. The predictions and the X-ray CT images are shown for each interface. Two predictions are displayed, the prediction above the X-ray image was obtained on the blind phase of the exercise and the predictions below were obtained on the correction phase. Note that the CT images on each interface contain some bleed through shading from neighboring interfaces. As seen in these figures the delamination extent was greatly over-predicted during the blind phase, even though some notional resemblance in shape could be conjectured. An algorithmic error was corrected during the second phase of the exercise, which resulted in the damage distributions shown in the bottom portion of Fig. 1. The corrected patterns are in much better agreement with experiment. A qualitative agreement between the experimental and DDM predicted matrix damage patterns was observed for all plies following the correction of the algorithm error.

The residual tensile and compression strength prediction and measurement results are shown on Fig. 2. Experimental data (black line), blind prediction results (blue line), corrected prediction results (red line) as well as pristine laminate static strength results

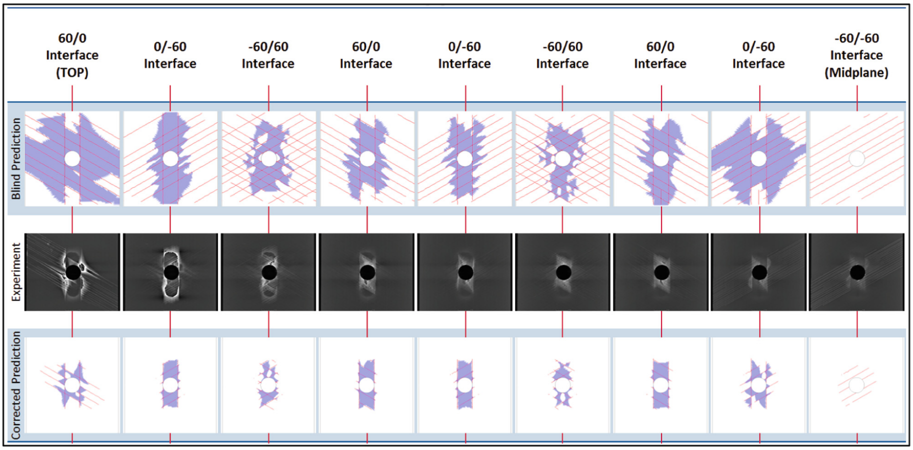

Fig. 1. Delamination extent in [60/0-60]3s laminate after 200,000 cycles

(green line) are shown. Consistent with the previous discussion, the stiffness of the laminates were considerably under predicted on the blind phase of the exercise, due to significant over prediction of matrix damage after fatigue cycling. However, the trends of the static strength change following fatigue loading were captured qualitatively correctly even during the blind prediction phase. According to DDM prediction the tensile strength significantly increased and the compression strength was relatively unchanged. The observed strength increase in tension was 24% and the predicted increase 49%. Such increase resulted from fiber direction stress concentration reduction because of splitting of the 0° ply and delamination on its interfaces. Large amounts of delamination in the laminate would indicate lower compression strength, however, these effects were apparently offset by the previously mentioned stress concentration reduction and resulted in practically unchanged values. The experimentally measured compression strength after fatigue cycling was also practically unchanged.

In summary, the DDM methodology has been extended to fatigue loading. A combination of cycle and event based progressive damage modeling algorithms has been implemented. The cohesive zone based fatigue algorithm has been explored and eliminates ambiguity or need for initial damage size or presence of any cracks or delaminations in the structure when impact damage is not present. Correct trends for residual tension and compressive static strength following fatigue loading can be predicted. Experimental data simulation results indicate the compressive strength remained relatively unchanged. Tensile strength indicated an increase, though the simulation results indicated a greater increase than the experimental data. Additional refinements in the simulation process will address this discrepancy.

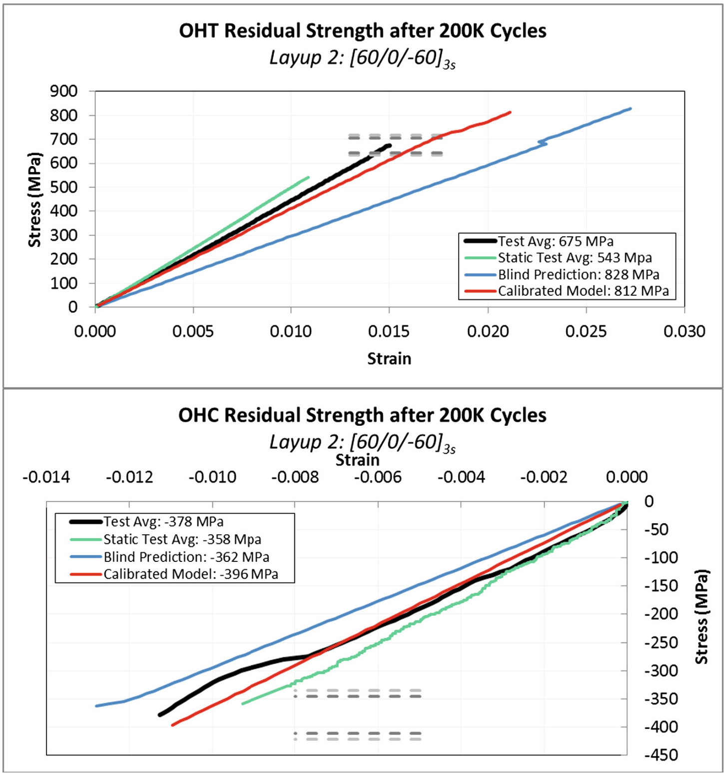

Fig. 2. Residual strength prediction after 200,000 cycle fatigue

3 NDE/I Damage Characterization

From the previous section, the modeling of damage progression is relatively mature in its development. However, input parameters to models of the damage state after an event, such as an impact, require NDE-based methods to measure the extent of the damage. Preliminary analysis could conclude that this is not a challenge with the large amount of literature addressing the use of NDE methods, such as ultrasound and thermography, for detecting delaminations from impact damage [Bossi and Georgeson 2018]. Many of these methods are used in operational environments which restrict access to only the external surface of a structure. As a representative illustration, Fig. 3 (a) shows the top view of a typical delamination imaged by an ultrasonic C-scan while Fig. 3(b) displays a three-dimensional rendering of the data, indicating a large amount of missing internal structure that cannot be detected by a one-sided ultrasonic technique. This is common for fielded NDE methods as they cannot detect damage that does not extend beyond damage in the previous laminate of the PMC. Delaminations block the interrogating energy from mechanical waves or thermal diffusion front from accessing additional regions of interest. Therefore, details inside the damaged area, including matrix cracks and smaller scale delaminations, are nearly impossible to detect from current one-sided NDE techniques.

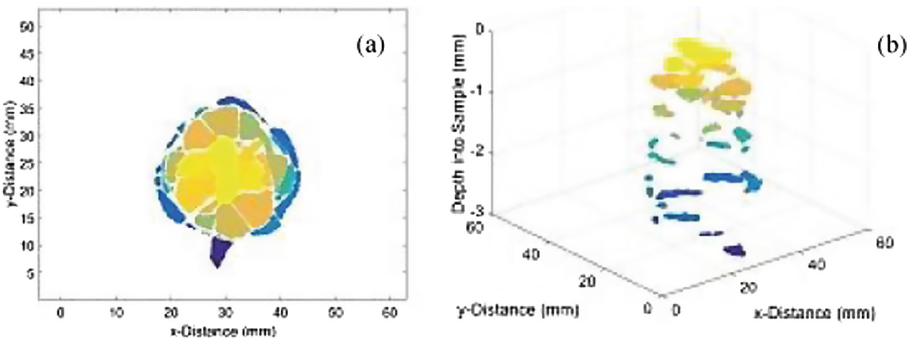

Fig. 3. (a) Top view of typical delamination imaged by ultrasonic C-scan, (b) Three-dimensional rendering of the ultrasonic C-scan data

To enable management of PMCs by a slow damage growth approach, additional details of the damage in three dimensions is required. Impact events in relatively thick PMC components can result in damage fields that do not expand outwards as a function of depth. To provide correct representations of existing damage fields in PMCs, as inputs for the initial material state in slow damage growth models, NDE-based methods must provide accurate metrics for 3D characterization of damage for its length, width, and depth. To enhance the accuracy of the approach, the NDE diagnostic capability should include information regarding the extent of matrix cracks, including their location and which plies are bridged by the cracks.

These attributes of damage characterization are quite challenging and represent a capability for NDE-based methods found only in laboratories to date. The best methods, as shown in Fig. 2, are based on X-ray CT methods. However, to obtain the desired data with sufficient fidelity, access to more than one surface is required and dye infiltration is typically applied to improve X-ray CT sensitivity. Thermal diffusion-based imaging methods have been explored, including tailored sources represented by timing and placement of thermal energy, to determine if variations in the thermal flow could be linked to features of the damage field that are not readily detected by flash-excitation based thermal imaging [Whitlow et al. 2018]. However, the lateral diffusion behavior of PMCs was found to inhibit such discrimination and mask features of hidden damage even in simple model-based assessment scenarios.

Another inspection modality that can penetrate into PMCs is ultrasonic-based methods. Initial exploration focused on evolving the well-known angle-beam shear wave method to access regions not readily accessible using traditional longitudinal wave methods. The concept for this approach is shown in Fig. 4 and includes both longitudinal waves to provide an estimate of the area of the damage and angle-beam shear waves to detect the extent of damage beneath the initial delaminations [Lindgren et al. 2015]. Preliminary efforts with this approach indicated some promise, but additional constraints limited its capability. The variations in the laminate lay-up introduced restrictions in the incident angle of the ultrasound and cause extensive scattering of the ultrasound as a function of its frequency and excitation amplitude.

To enhance the exploration process, model-based methods were used including both finite element and analytical methods. As inputs to these simulations, several test samples with known impact energies were metallurgically characterized using a serial

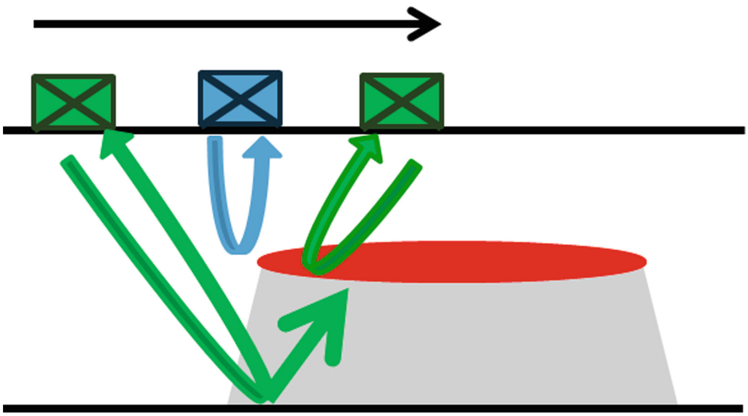

Fig. 4. Initial concepts for ultrasonic interrogation of three dimensional damage in PMCs

sectioning technique that enables full three dimensional reconstruction of the internal damage [Wallentine and Uchic 2018]. A representative image from this characterization is shown in Fig. 5.

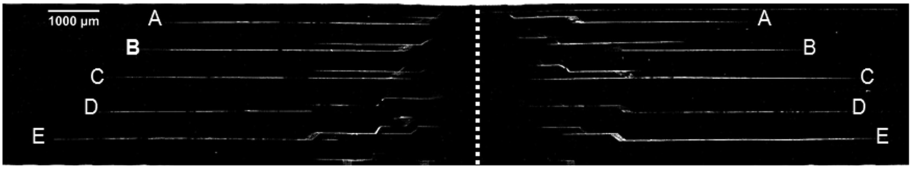

Fig. 5. Representative single plane of three dimensional characterization of a PMC impact showing ply-by-ply damage

Using simulations-based methods, alternative incident angles were tested to determine which approach revealed the most information regarding the internal features of the damaged area. Various oblique angle approaches were evaluated to determine if meaningful reflections could be obtained from the external edges of the delaminations. While some promise was shown in various simulations, the experimental data collected to date appears to indicate the localized scattering within the PMC inhibits detection of meaningful signals, even with advanced signal processing techniques [Welter et al. 2019].

Additional simulation efforts focused on single-sided pitch-catch methods where the ultrasound was mapped as it propagated through the damage area of the PMC [Aldrin et al. 2019]. A representative numerical model result is shown in Fig. 6 and includes transmitted and reflective quasi-longitudinal and quasi-shear modes propagating in the PMC. With this approach, signal amplitude was found to be dependent on the severity of damage. To ensure the ultrasound was propagating through the damaged region and not on the external surfaces, various dampening elements were placed on the surfaces to prevent coupled sound from propagating through along these surfaces.

In addition, specialized test fixtures were developed to enable immersion-based exploration on one surface while ensuring the opposite surface was not immersed to represent the boundary conditions found on actual aerospace components.

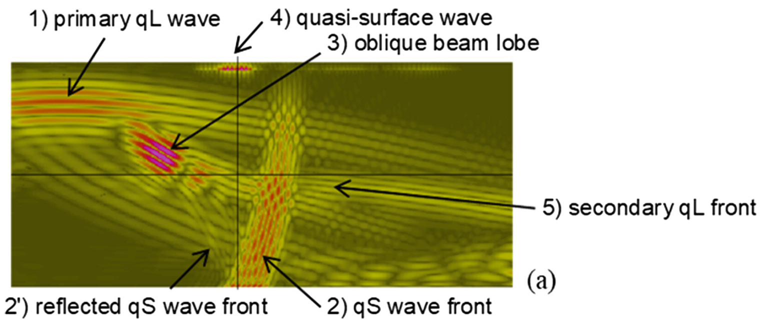

Fig. 6. Representative analytical modeling results illustrating multiple ultrasonic modes in a PMC test sample.

The latest results indicate promise to develop practical methods to assess the magnitude and extent of damage in PMCs from impact events. It is expected that these methods can be extended to other forms of damage, such as fatigue after impact. Additional development of the approach is required for transition, but the results to date illustrate the potential of using ultrasound to characterize internal features in three dimensions, building off of prior work addressing two-dimensional fatigue cracks in metals [Aldrin and Forsyth 2017]. Topics identified for additional exploration include optimization of the excitation and detection angles and frequencies as a function of PMC lay-up, thickness, and geometry. Model-based methods will be used for these investigations as the rate of discovery is accelerated with these approaches even with the sometimes long computational runs required to address the complexity of PMCs. Another item being actively pursued is the incorporation of various array transducer configurations, including both dense and sparse arrays, to provide the greatest area of coverage while ensuring the incident and detection angles required for interrogating the hidden damage region are maintained.

Another item being explored is how to provide metrics of accuracy in the measurement capability. As mentioned previously, for DADT of metals the input to the risk calculation is the probability of detection curve for fatigue cracks determined by processes recommended in MIL HDBK 1823A. Equivalent metrics of area and depth of damage are required for PMC damage characterization. Initial efforts have been completed to demonstrate how such metrics could be developed [Aldrin et al. 2014], but it is not clear how much these approaches will be relevant for the types of damage and the areas of interest in PMCs. However, as the work in refining the characterization methods continues, the development of metrics to assess the accuracy of these measurements will be pursued. This will ensure the developed capability can be integrated into USAF processes for structural risk calculations and ensure the integrity of PMC structures.

4 Summary

The use of PMCs in aircraft structures continue to grow and are growing in their application to structural applications as primary load carrying elements. Current certification processes for PMCs are aligned with "safe-life" approaches. There is a growing interest in developing DADT equivalent for PMCs as is being used today for metallic primary structure. To realize this objective, the elements to enable a slow-damage growth method for PMCs are being developed. This includes the development of damage growth models for both static and fatigue strength. In addition, these models must include and address additional damage modes, such as impact damage. Work to date has shown these models to be effective in matching various damage modes through blind studies on test samples subjected to various damage modes and loading conditions.

Parallel to the evolution of slow damage growth models, NDE-based methods need to be developed to characterize the damage present as an input parameter to damage growth models to enable them to work properly, especially after impact damage. Several constraints present challenges for possible NDE techniques, included limited access to a single surface and the overall complexity in both the internal configuration and the geometry of PMC structures. A combination of finite element and analytical modeling has been performed to explore various methods to assess damage internal to PMCs, including both thermal diffusion and ultrasonic approaches. Results to date indicate single-sided pitch catch approaches hold the highest potential to enable the desired characterization to be accomplished. Work continues to mature these methods, including development of methods to provide metrics of accuracy in damage characterization similar to current practices of determining fatigue crack detection in metals using probability of detection. The additional challenge for PMCs is the need for these statistical metrics of performance to assess all parameters that provide three dimensional characterization. Progress is being realized on all aspects of this challenge and the potential to manage PMCs using a DADT approach seems attainable in the near future.

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